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(54) **DISTRIBUTED POWER SYSTEM USING DIRECT CURRENT POWER SOURCES**

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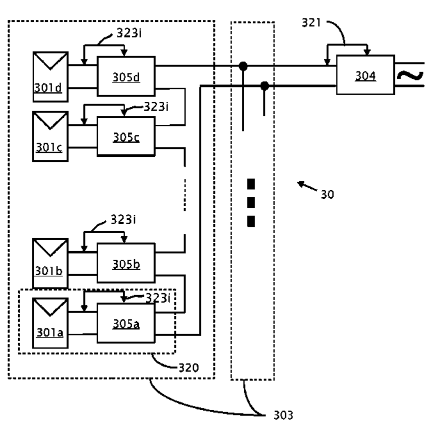
(57) **ABSTRACT**

A distributed power system including multiple (DC) batteries each DC battery with positive and negative poles. Multiple power converters are coupled respectively to the DC batteries. Each power converter includes a first terminal, a second terminal, a third terminal and a fourth terminal. The first terminal is adapted for coupling to the positive pole. The second terminal is adapted for coupling to the negative pole. The power converter includes: (i) a control loop adapted for setting the voltage between or current through the first and second terminals, and (ii) a power conversion portion adapted to selectively either: convert power from said first and second terminals to said third and fourth terminals to discharge the battery connected thereto, or to convert power from the third and fourth terminals to the first and second terminals to charge the battery connected thereto. Each of the power converters is adapted for serial connection to at least one other power converter by connecting respectively the third and fourth terminals, thereby forming a serial string. A power controller is adapted for coupling to the serial string. The power controller includes a control part adapted to maintain current through or voltage across the serial string at a predetermined value.

20 Claims, 12 Drawing Sheets



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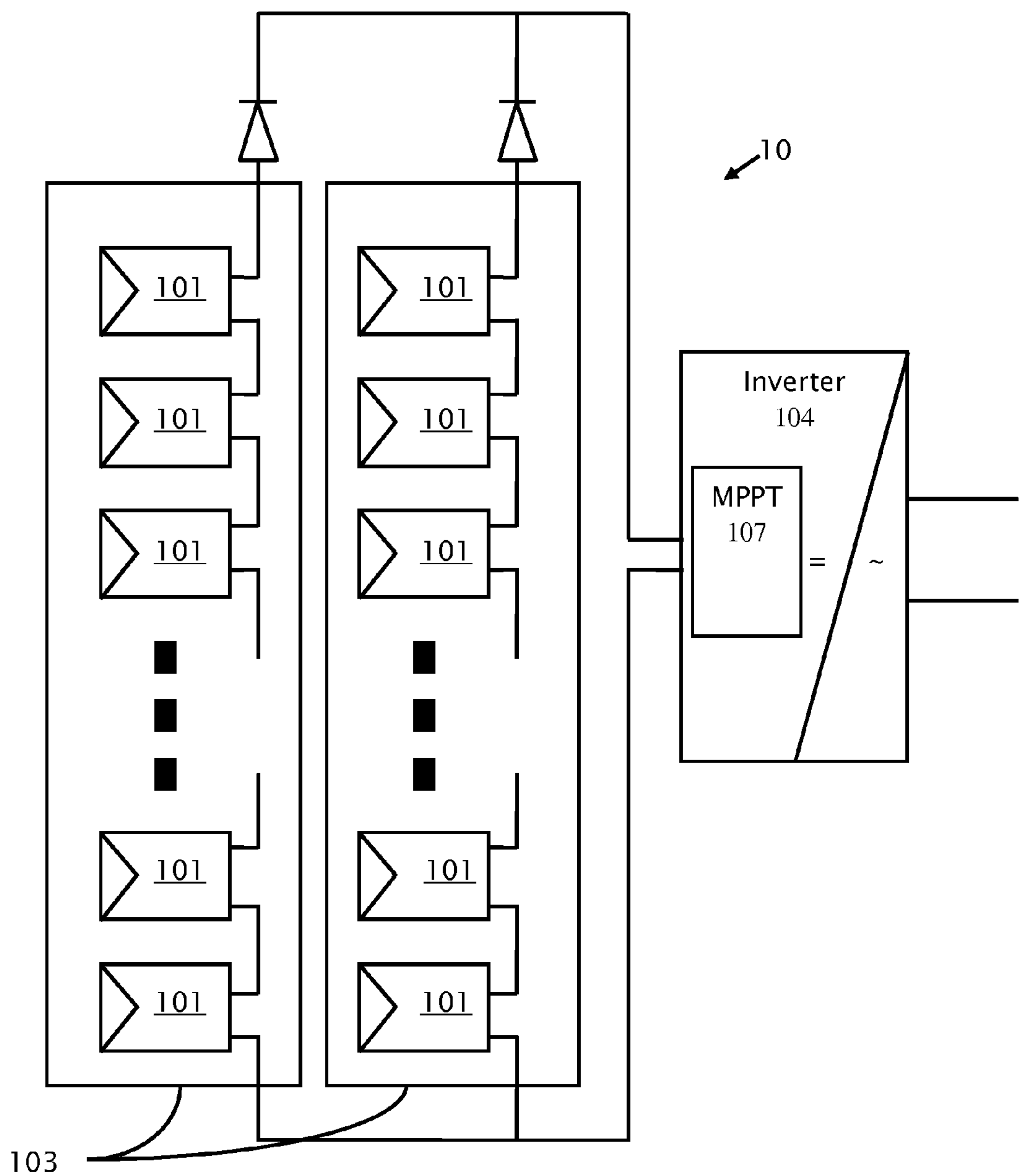


Fig. 1 Conventional Art

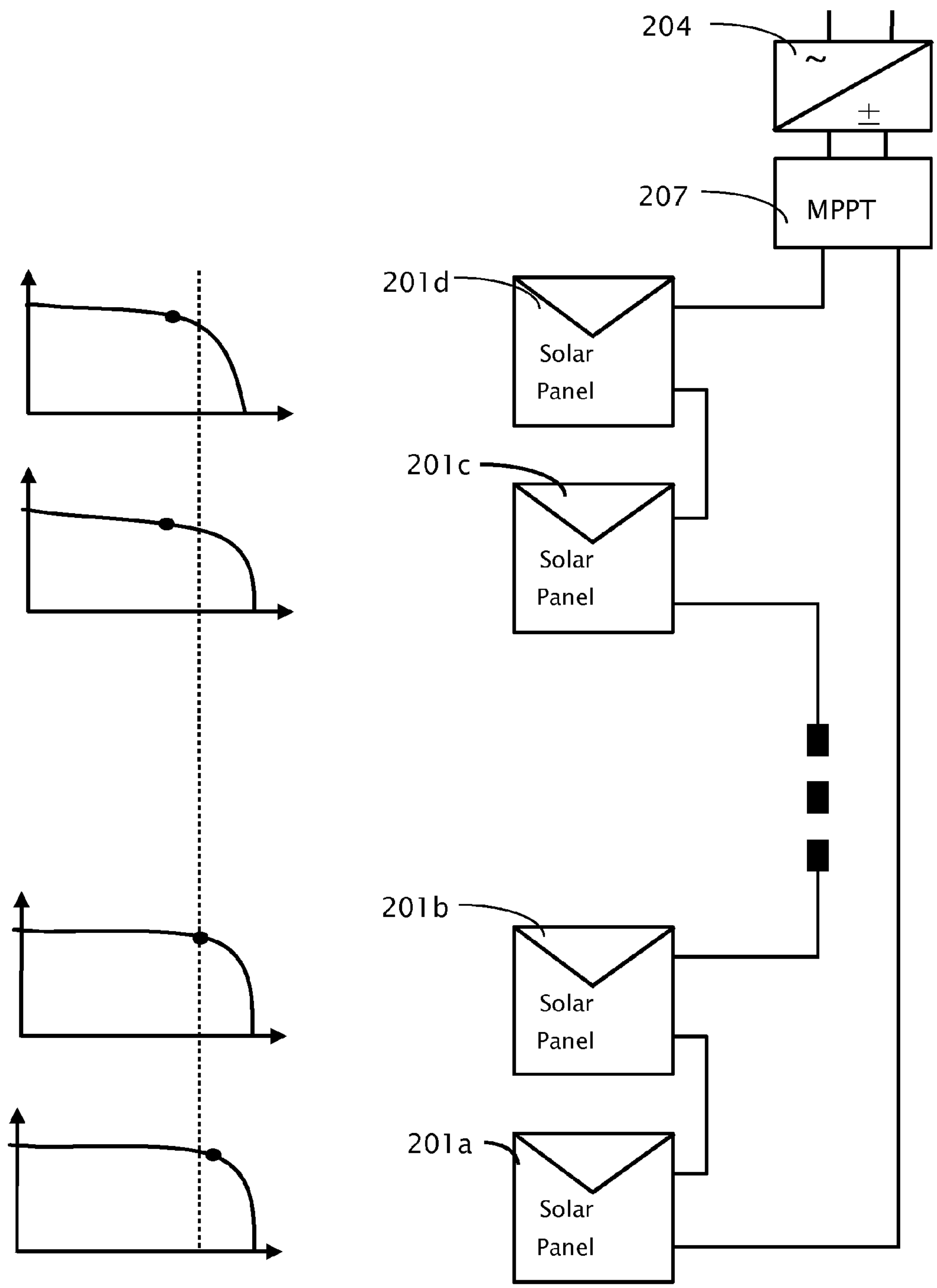
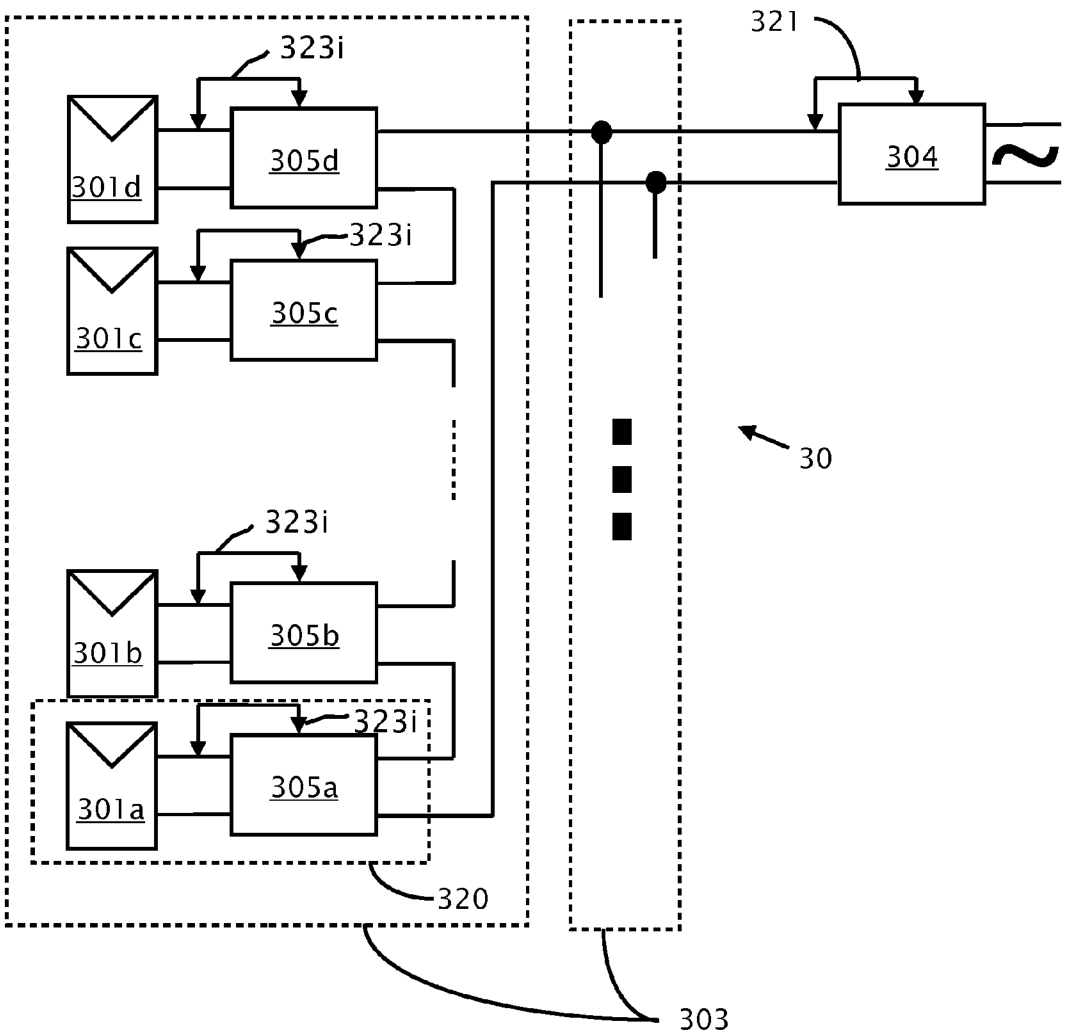


Fig. 2 Conventional Art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305d
301d
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305c
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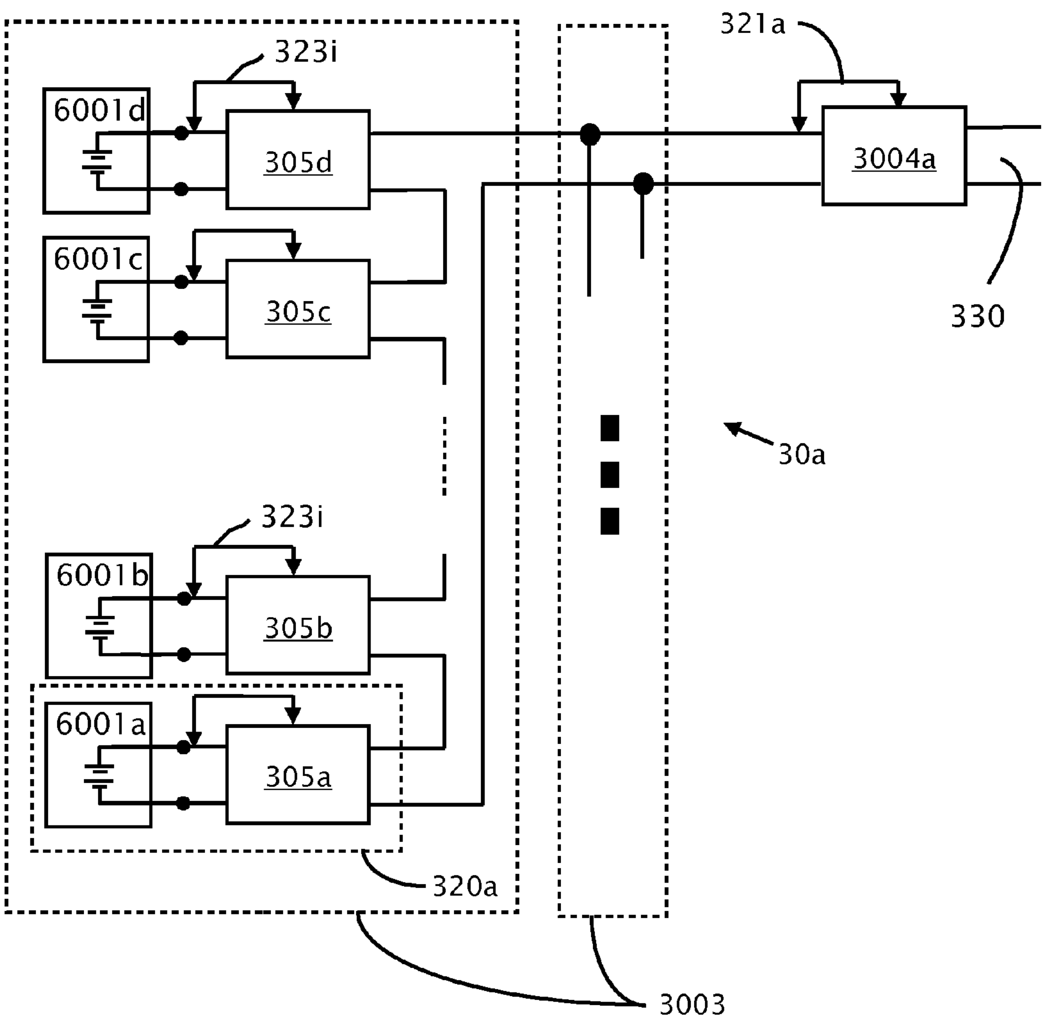
30
303

Figure 3



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323i
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305c
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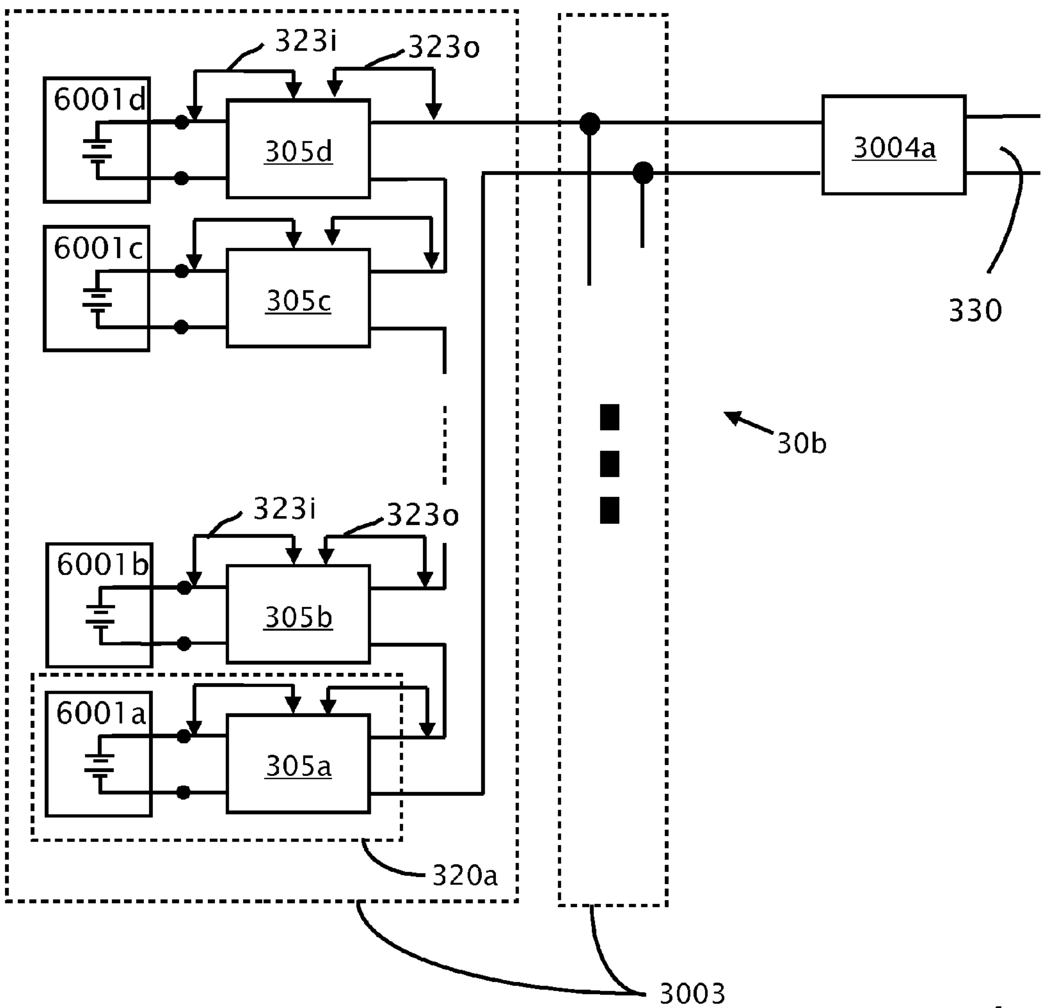
320a
3003

Figure 3a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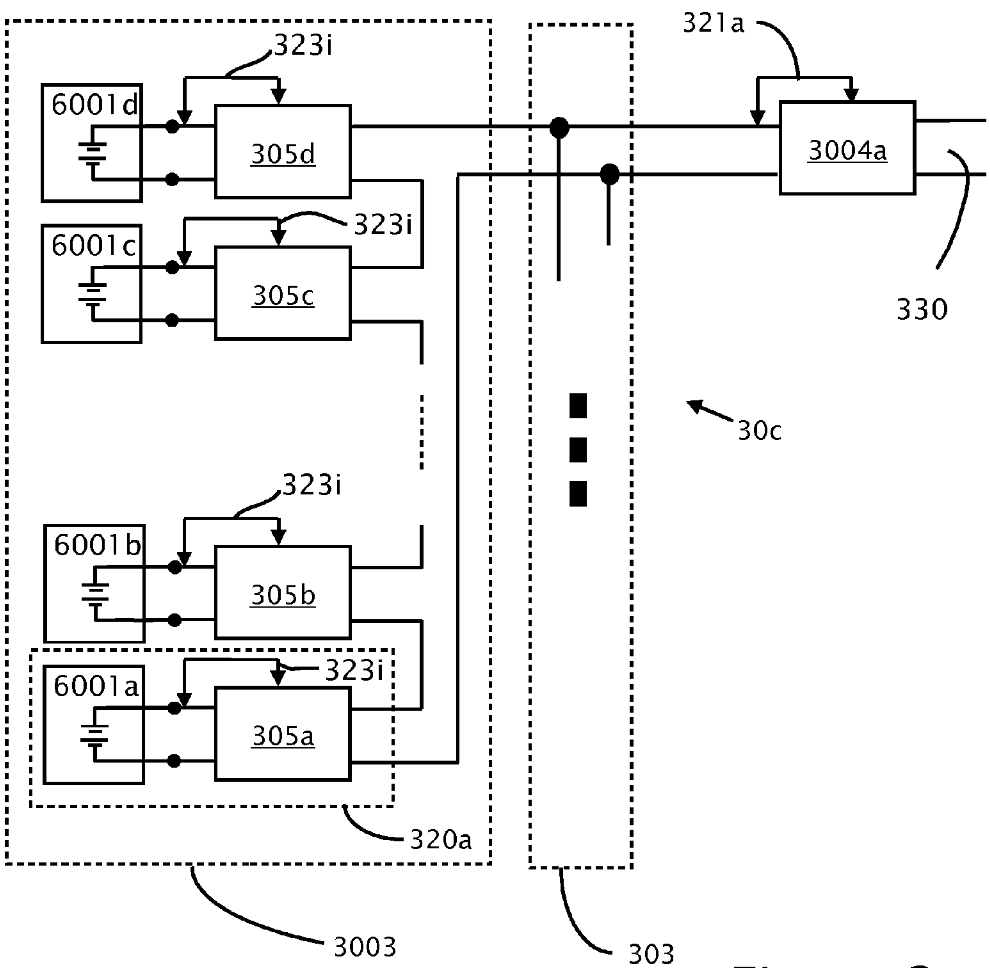
305a
320a
3003

Figure 3b



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3003
303

Figure 3c

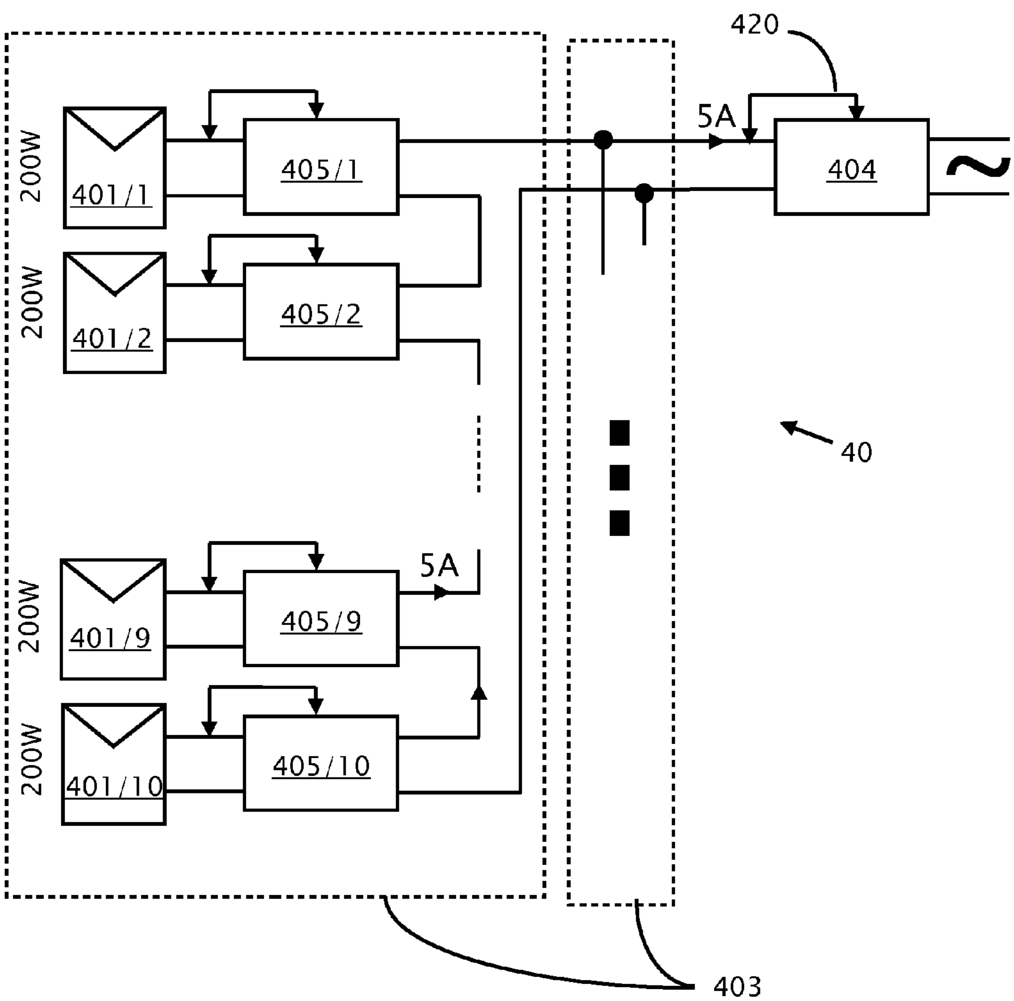
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Figure 4A

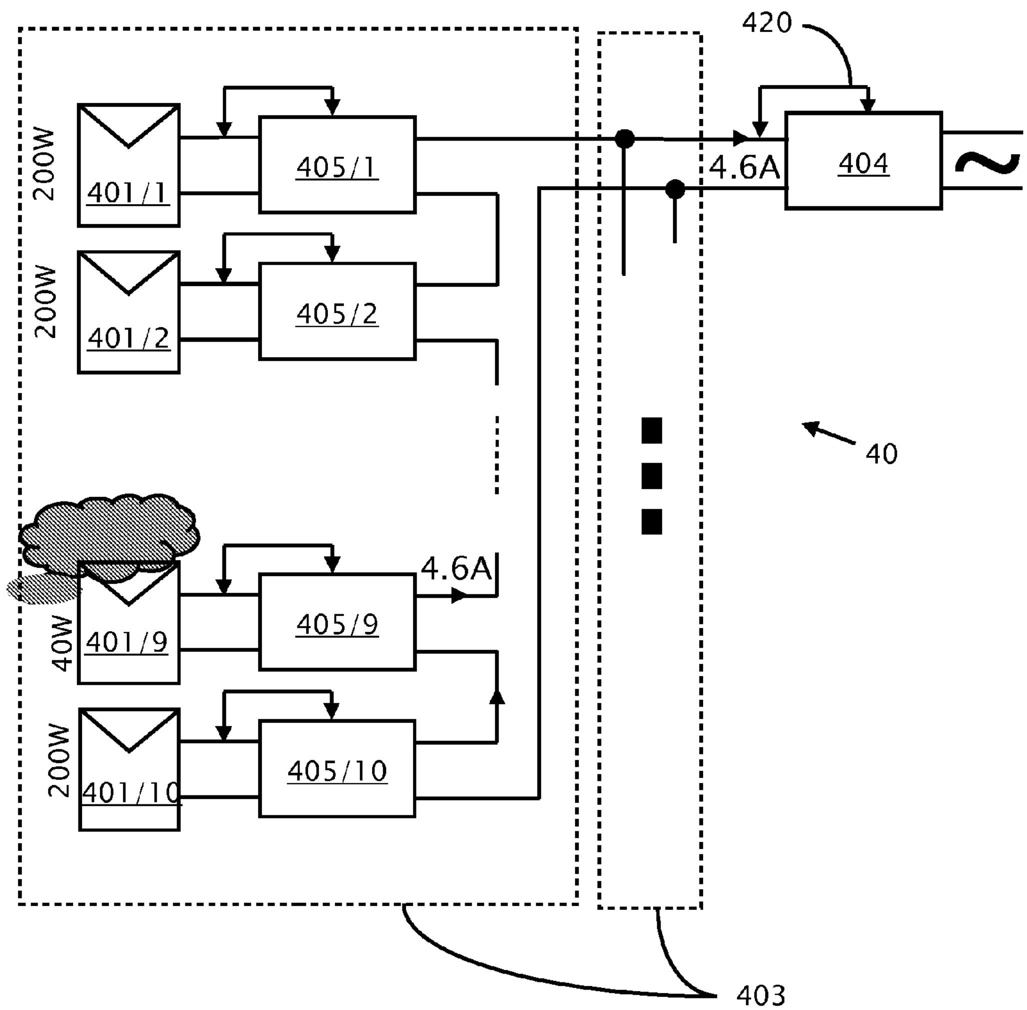
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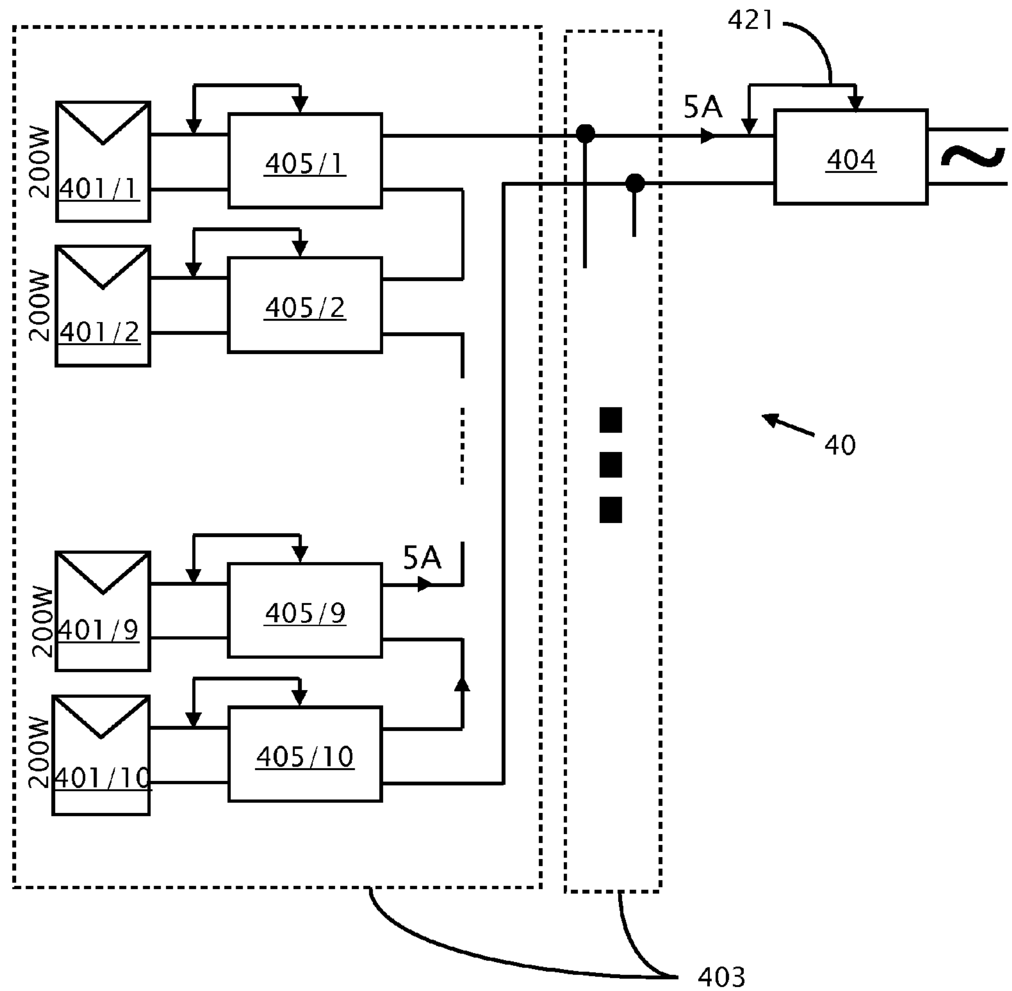
Figure 4B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403

Figure 4C

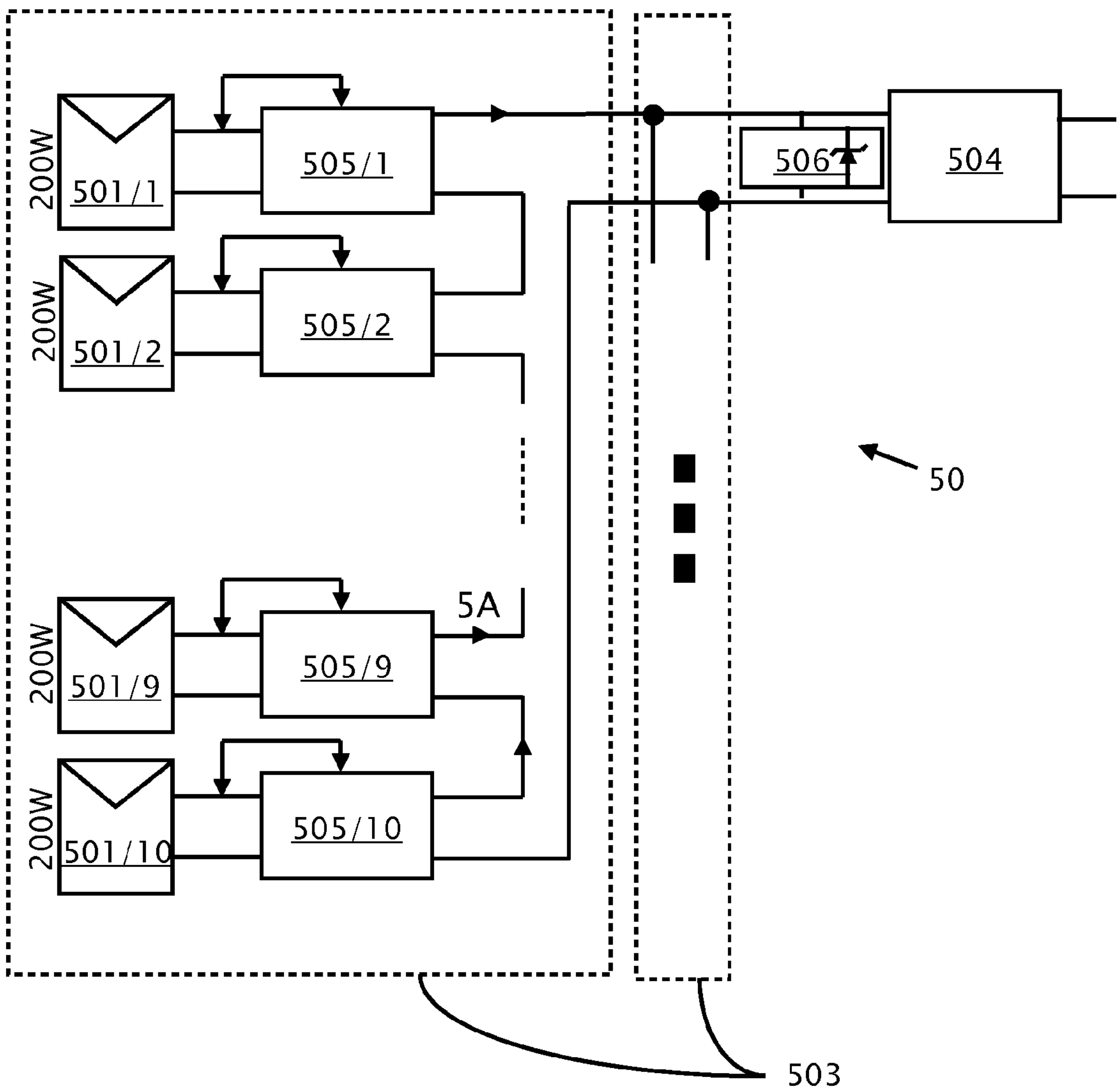

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Figure 5

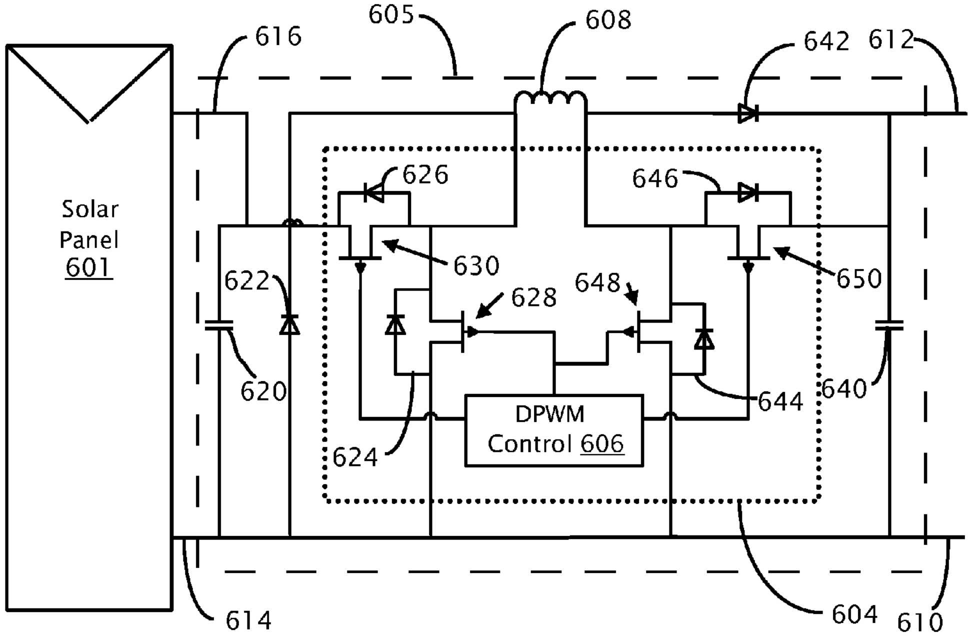


Figure 6

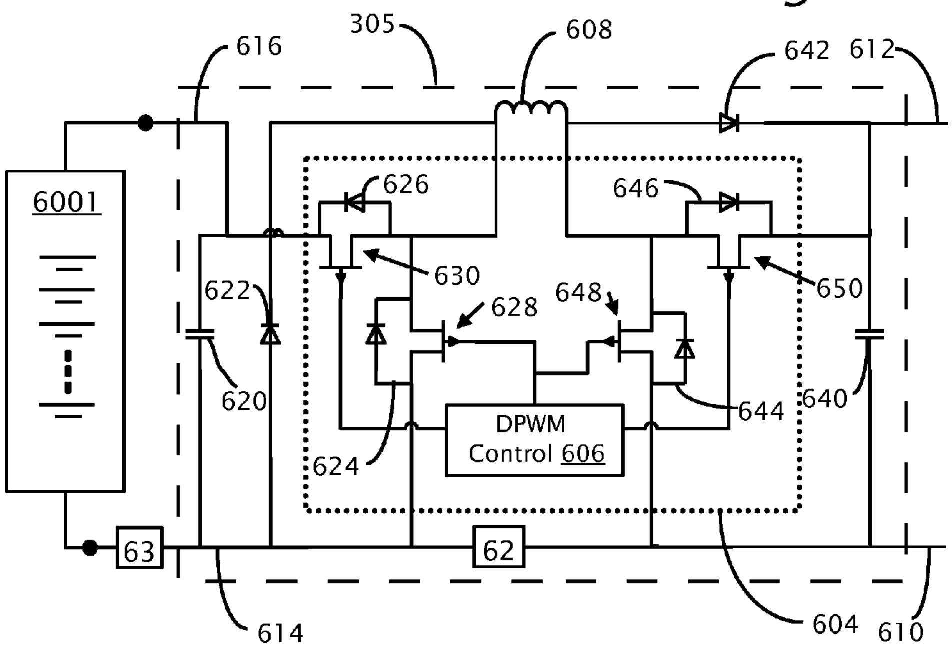
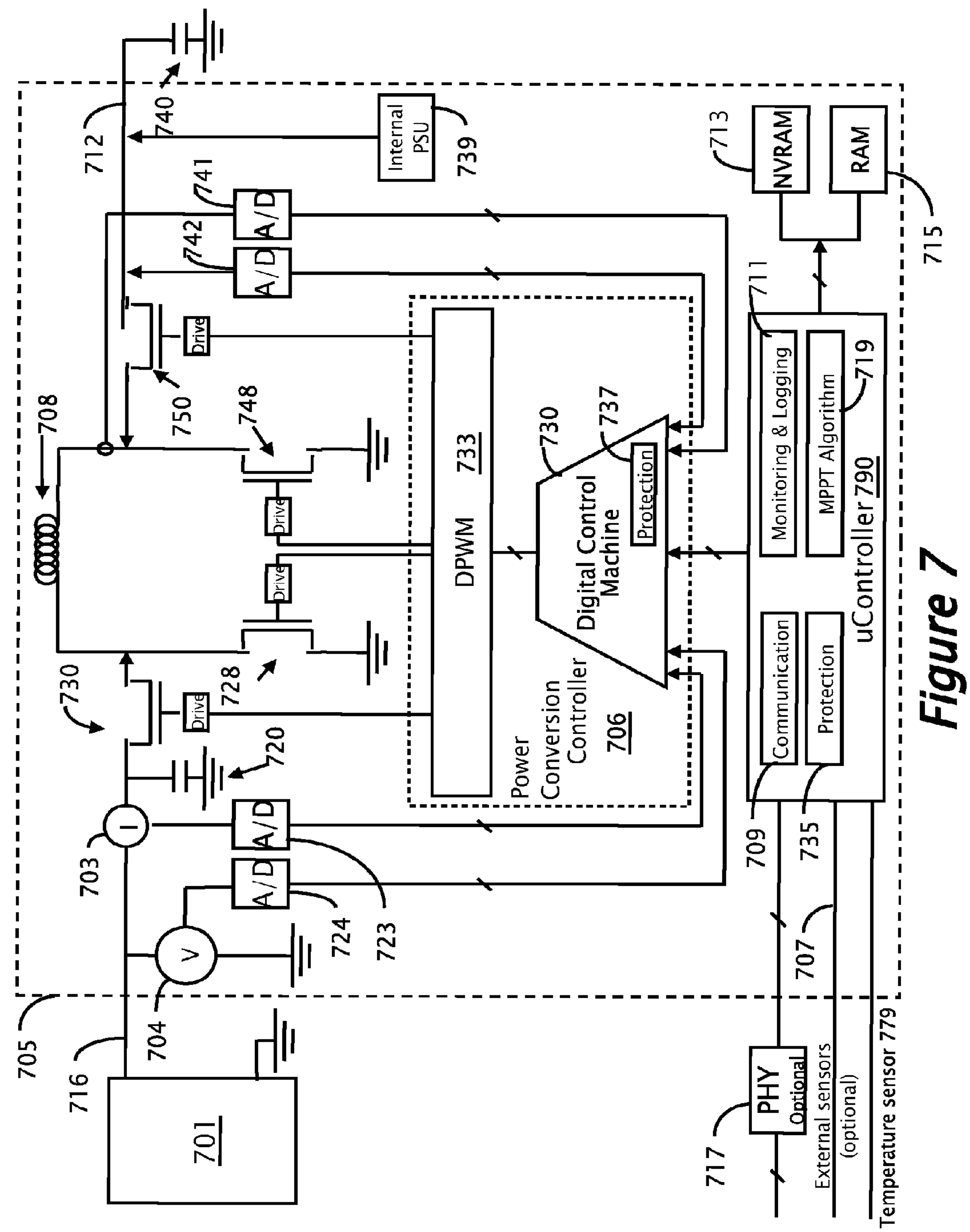


Figure 6a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A/D
741
A/D
712
740
Internal PSU
739
DPWM
733
Power Conversion Controller
706
Digital Control Machine
Protection
730
737
Monitoring & Logging
MPPT Algorithm
719
711
Communication
Protection
uController 790
709
735
707
NVRAM
RAM
713
715
PHY
Optional
717
External sensors
(optional)
Temperature sensor 779

Figure 7

DISTRIBUTED POWER SYSTEM USING DIRECT CURRENT POWER SOURCES

CROSS REFERENCE TO RELATED APPLICATIONS

The present application is a continuation of U.S. patent application Ser. No. 12/911,153, filed Oct. 25, 2010, and entitled "Distributed Power System Using Direct Current Power Sources," which is a continuation-in-part of U.S. patent application Ser. No. 11/950,271, filed Dec. 4, 2007, and entitled "Distributed Power Harvesting Systems Using DC Power Sources," and which claims the benefit of U.S. Provisional Patent Application No. 61/254,681, filed Oct. 24, 2009, and entitled "Distributed Converter Architecture For Battery Banks," each of which are incorporated by reference herein in their entirety for all purposes.

BACKGROUND

1. Technical Field

The field of the invention relates generally to power production from distributed DC power sources, and more particularly to management of distributed DC power sources in series installations.

2. Description of Related Art

The recent increased interest in renewable energy has led to increased research in systems for distributed generation of energy, such as photovoltaic cells (PV), fuel cells, batteries (e.g., for hybrid cars), etc. Various topologies have been proposed for connecting these power sources to the load, taking into consideration various parameters, such as voltage/current requirements, operating conditions, reliability, safety, costs, etc. For example, most of these sources provide low voltage output (normally a few volts for one cell, or a few tens of volts for serially connected cells), so that many of them need to be connected serially to achieve the required operating voltage. Conversely, a serial connection may fail to provide the required current, so that several strings of serial connections may need to be connected in parallel to provide the required current.

It is also known that power generation from each of these sources depends on manufacturing, operating, and environmental conditions. For example, various inconsistencies in manufacturing may cause two identical sources to provide different output characteristics. Similarly, two identical sources may react differently to operating and/or environmental conditions, such as load, temperature, etc. In practical installations, different source may also experience different environmental conditions, e.g., in solar power installations some panels may be exposed to full sun, while others be shaded, thereby delivering different power output. In a multiple-battery installation, some of the batteries may age differently, thereby delivering different power output. While these problems and the solutions provided by the subject invention are applicable to any distributed power system, the following discussion turns to solar energy so as to provide better understanding by way of a concrete example.

A conventional installation of solar power system **10** is illustrated in FIG. **1**. Since the voltage provided by each individual solar panel **101** is low, several panels are connected in series to form a string of panels **103**. For a large installation, when higher current is required, several strings **103** may be connected in parallel to form the overall system **10**. The solar panels are mounted outdoors, and their leads are connected to a maximum power point tracking (MPPT) module **107** and then to an inverter **104**. The MPPT **107** is typically implemented as part of the inverter **104**. The harvested power from the DC sources is delivered to the inverter **104**, which converts the fluctuating direct-current (DC) into alternating-current (AC) having a desired voltage and frequency, which is usually 110V or 220V at 60 Hz, or 220V at 50 Hz (It is interesting to note the even in the US many inverters produce 220V, which is then split into two 110V feeds in the electric box). The AC current from the inverter **104** may then be used for operating electric appliances or fed to the power grid. Alternatively, if the installation is not tied to the grid, the power extracted from the inverter may be directed to a conversion and charge/discharge circuit to store the excess power created as charge in batteries. In case of a battery-tied application, the inversion stage might be skipped altogether, and the DC output of the MPPT stage **107** may be fed into the charge/discharge circuit.

As noted above, each solar panel **101** supplies relatively very low voltage and current. The problem facing the solar array designer is to produce a standard AC current at 120V or 220V root-mean-square (RMS) from a combination of the low voltages of the solar panels. The delivery of high power from a low voltage requires very high currents, which cause large conduction losses on the order of the second power of the current (I^2). Furthermore, a power inverter, such as the inverter **104**, which is used to convert DC current to AC current, is most efficient when its input voltage is slightly higher than its output RMS voltage multiplied by the square root of 2. Hence, in many applications, the power sources, such as the solar panels **101**, are combined in order to reach the correct voltage or current. The most common method connects the power sources in series in order to reach the desirable voltage and in parallel in order to reach the desirable current, as shown in FIG. **1**. A large number of the panels **101** are connected into a string **103** and the strings **103** are connected in parallel to the power inverter **104**. The panels **101** are connected in series in order to reach the minimal voltage required for the inverter. Multiple strings **103** arc connected in parallel into an array to supply higher current, so as to enable higher power output.

While this configuration is advantageous in terms of cost and architecture simplicity, several drawbacks have been identified in the literature for such architecture. One recognized drawback is inefficiencies cause by non-optimal power draw from each individual panel, as explained below. As explained above, the output of the DC power sources is influenced by many conditions. Therefore, to maximize the power draw from each source, one needs to draw the combination of voltage and current that provides the peak power for the currently prevailing conditions. As conditions change, the combination of voltage and current draw may need to be changed as well.

FIG. **2** illustrates one serial string of DC sources, e.g., solar panels **201***a*-**201***d*, connected to MPPT circuit **207** and inverter **204**. The current versus voltage (IV) characteristics plotted (**210***a*-**210***d*) to the left of each DC source **201**. For each DC source **201**, the current decreases as the output voltage increases. At some voltage value the current goes to zero, and in some applications may assume a negative value, meaning that the source becomes a sink. Bypass diodes are used to prevent the source from becoming a sink. The power output of each source **201**, which is equal to the product of current and voltage (P=I*V), varies depending on the voltage drawn from the source. At a certain current and voltage, close to the falling off point of the current, the power reaches its maximum. It is desirable to operate a power generating cell at this maximum power point. The purpose of the MPPT is to find this point and operate the system at this point so as to draw the maximum power from the sources.

In a typical, conventional solar panel array, different algorithms and techniques are used to optimize the integrated power output of the system **10** using the MPPT module **107**. The MPPT module **107** receives the current extracted from all of the solar panels together and tracks the maximum power point for this current to provide the maximum average power such that if more current is extracted, the average voltage from the panels starts to drop, thus lowering the harvested power. The MPPT module **107** maintains a current that yields the maximum average power from the overall system **10**.

However, since the sources **201***a*-**201***d* are connected in series to a single MPPT **207**, the MPPT must select a single point, which would be somewhat of an average of the MPP of the serially connected sources. In practice, it is very likely that the MPPT would operate at an I-V point that is optimum to only a few or none of the sources. In the example of FIG. **2**, the selected point is the maximum power point for source **201***b*, but is off the maximum power point for sources **201***a*, **201***c* and **201***d*. Consequently, the arrangement is not operated at best achievable efficiency.

Turning back to the example of a solar system **10** of FIG. **1**, fixing a predetermined constant output voltage from the strings **103** may cause the solar panels to supply lower output power than otherwise possible. Further, each string carries a single current that is passed through all of the solar panels along the string. If the solar panels are mismatched due to manufacturing differences, aging or if they malfunction or are placed under different shading conditions, the current, voltage and power output of each panel will be different. Forcing a single current through all of the panels of the string causes the individual panels to work at a non-optimal power point and can also cause panels which are highly mismatched to generate "hot spots" due to the high current flowing through them. Due to these and other drawbacks of conventional centralized methods, the solar panels have to be matched properly. In some cases external diodes are used to bypass the panels that are highly mismatched. In conventional multiple string configurations all strings have to be composed of exactly the same number of solar panels and the panels are selected of the same model and must be install at exactly the same spatial orientation, being exposed to the same sunlight conditions at all times. This is difficult to achieve and can be very costly.

BRIEF SUMMARY

According to embodiments of the present invention there is provided a distributed power system including multiple (DC) batteries each DC battery with positive and negative poles. Multiple power converters are coupled respectively to the DC batteries. Each power converter includes a first terminal, a second terminal, a third terminal and a fourth terminal. The first terminal is adapted for coupling to the positive pole. The second terminal is adapted for coupling to the negative pole. The power converter includes: (i) a control loop adapted for setting the voltage between or current through the first and second terminals, and (ii) a power conversion portion adapted to selectively either: convert power from said first and second terminals to said third and fourth terminals to discharge the battery connected thereto, or to convert power from the third and fourth terminals to the first and second terminals to charge the battery connected thereto.

Each of the power converters is adapted for serial connection to at least one other power converter by connecting respectively the third and fourth terminals, thereby forming a serial string. A power controller is adapted for coupling to the serial string. The power controller includes a control part adapted to maintain current through or voltage across the serial string at a predetermined value. The control part may maintain voltage across the serial string at a predetermined value or the control part may maintain current through the serial string at a predetermined value. The power controller may include a bidirectional DC/AC inverter or bi-directional DC/DC converter. The power converters may function as a current source, voltage regulator or trickle charge source. The distributed power system may further include multiple photovoltaic panels; multiple DC-DC converters. Each of the DC-to-DC converters may include input terminals coupled to a respective DC photovoltaic panels and output terminals coupled in series to the other DC-to-DC converters, thereby forming a second serial string. A control loop sets the voltage and/or current at the input terminals of the DC-to-DC converter according to predetermined criteria. A power conversion portion converts the power received at the input terminals to an output power at the output terminals. The serial string and the second serial string are connectible in parallel to form parallel-connected strings. A power controller may be adapted for coupling in parallel to the parallel-connected strings, the power controller including a control part adapted to maintain current through or voltage across the parallel connected strings at a predetermined value. The power controller may be off-grid (not connected to the grid) or connected to the grid. The photovoltaic panels may provide electrical power for charging the batteries.

According to embodiments of the present invention there is provided a distributed power system including multiple (DC) batteries each DC battery with positive and negative poles. Multiple power converters are coupled respectively to the DC batteries. Each power converter includes a first terminal, a second terminal, a third terminal and a fourth terminal. The first terminal is adapted for coupling to the positive pole. The second terminal is adapted for coupling to the negative pole. The power converter includes a first control loop configured to set either current through or voltage between the first and second terminals, and a second control loop configured set either current through or voltage between the third and fourth terminals; and (iii) a power conversion portion adapted to selectively either: convert power from the first and second terminals to the third and fourth terminals to discharge the battery connected thereto, or to convert power from the third and fourth terminals to the first and second terminals to charge the battery connected thereto; wherein each of the power converters is adapted for serial connection to at least one other power converter by connecting respectively the third and fourth terminals, thereby forming a serial string. The distributed power system may further include multiple photovoltaic panels and multiple DC-DC converters. Each of the DC-to-DC converters may include input terminals coupled to a respective DC photovoltaic panels and output terminals coupled in series to the other DC-to-DC converters, thereby forming a second serial string. A control loop sets the voltage and/or current at the input terminals of the DC-to-DC converter according to predetermined criteria. A power conversion portion converts the power received at the input terminals to an output power at the output terminals. The serial string and the second serial string are connectible in parallel to form parallel-connected strings. The power controller is selectably either off-grid or connected to grid. The photovoltaic panels may provide electrical power for charging the batteries. A communications interface between the power controller and the power converters may be used for controlling charging and discharging of the batteries.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is herein described, by way of example only, with reference to the accompanying drawings, wherein:

FIG. **1** illustrates a conventional centralized power harvesting system using DC power sources.

FIG. **2** illustrates current versus voltage characteristic curves for one serial string of DC sources.

FIG. **3** illustrates a distributed power harvesting system, according to aspects of the invention, using DC power sources.

FIGS. **3***a*-**3***c* show variations of distributed power systems using DC batteries according to a different embodiments of the present invention.

FIGS. **4**A and **4**B illustrate the operation of the system of FIG. **3** under different conditions, according to aspects of the invention.

FIG. **4**C illustrates an embodiment of the invention wherein the inverter controls the input current.

FIG. **5** illustrates a distributed power harvesting system, according to other aspects of the invention, using DC power sources.

FIG. **6** illustrates an exemplary DC-to-DC converter according to aspects of the invention.

FIG. **6***a* shows a slightly modified DC-DC converter based on the DC-DC converter shown in FIG. **6**, according to an embodiment of the present invention.

FIG. **7** illustrates a power converter, according to aspects of the invention including control features of the aspects of the invention.

DETAILED DESCRIPTION

Reference will now be made in detail to embodiments of the present invention, examples of which are illustrated in the accompanying drawings, wherein like reference numerals refer to the like elements throughout. The embodiments are described below to explain the present invention by referring to the figures.

Before explaining embodiments of the invention in detail, it is to be understood that the invention is not limited in its application to the details of design and the arrangement of the components set forth in the following description or illustrated in the drawings. The invention is capable of other embodiments or of being practiced or carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein is for the purpose of description and should not be regarded as limiting.

The topology provided by the subject invention solves many of the problems associated with, and has many advantages over, the conventional art topologies. For example, the inventive topology enables serially connecting mismatched power sources, such as mismatched solar panels, panel of different models and power ratings, and even panels from different manufacturers and semiconductor materials. It allows serial connection of sources operating under different conditions, such as, e.g., solar panels exposed to different light or temperature conditions. It also enables installations of serially connected panels at different orientations or different sections of the roof or structure. This and other features and advantages will become apparent from the following detailed description. Aspects of the present invention provide a system and method for combining power from multiple DC power sources into a single power supply. According to aspects of the present invention, each DC power source is associated with a DC-DC power converter. Modules formed by coupling the DC power sources to their associated converters are coupled in series to provide a string of modules. The string of modules is then coupled to an inverter having its input voltage fixed. A maximum power point control loop in each converter harvests the maximum power from each DC power source and transfers this power as output from the power converter. For each converter, substantially all the input power is converted to the output power, such that the conversion efficiency may be 90% or higher in some situations. Further, the controlling is performed by fixing the input current or input voltage of the converter to the maximum power point and allowing output voltage of the converter to vary. For each power source, one or more sensors perform the monitoring of the input power level to the associated converter. In some aspects of the invention, a microcontroller may perform the maximum power point tracking and control in each converter by using pulse width modulation to adjust the duty cycle used for transferring power from the input to the output.

One aspect of the present invention provides a greater degree of fault tolerance, maintenance and serviceability by monitoring, logging and/or communicating the performance of each solar panel. In one aspect of the invention, the microcontroller that is used for maximum power point tracking, may also be used to perform the monitoring, logging and communication functions. These functions allow for quick and easy troubleshooting during installation, thereby significantly reducing installation time. These functions are also beneficial for quick detection of problems during maintenance work. Aspects of the present invention allow easy location, repair, or replacement of failed solar panels. When repair or replacement is not feasible, bypass features of the current invention provide increased reliability.

In one aspect, the present invention relates to arrays of solar cells where the power from the cells is combined. Each converter may be attached to a single solar cell, or a plurality of cell connected in series, in parallel, or both, e.g., parallel connection of strings of serially connected cells. In one embodiment each converter is attached to one panel of photovoltaic strings. However, while applicable in the context of solar power technology, the aspects of the present invention may be used in any distributed power network using DC power sources. For example, they may be used in batteries with numerous cells or hybrid vehicles with multiple fuel cells on board The DC power sources may be solar cells, solar panels, electrical fuel cells, electrical batteries, and the like. Further, although the discussion below relates to combining power from an array of DC power sources into a source of AC voltage, the aspects of the present invention may also apply to combining power from DC sources into another DC voltage.

FIG. **3** illustrates a distributed power harvesting configuration **30**, according to an embodiment of the present invention. Configuration **30** enables connection of multiple power sources, for example solar panels **301***a*-**301***d*, to a single power supply. In one aspect of the invention, the series string of all of the solar panels may be coupled to an inverter **304**. In another aspect of the invention, several serially connected strings of solar panels may be connected to a single inverter **304**. The inverter **304** may be replaced by other elements, such as, e.g., a charging regulator for charging a battery bank.

In configuration **30**, each solar panel **301***a*-**301***d* is connected to a separate power converter circuit **305***a*-**305***d*. One solar panel together with its associated power converter circuit forms a module, e.g., module **320**. Each converter **305***a*-**305***d* adapts optimally to the power characteristics of the connected solar panel **301***a*-**301***d* and transfers the power efficiently from converter input to converter output. The converters **305***a*-**305***d* can be buck converters, boost converters, buck/boost converters, flyback or forward converters, etc.

The converters **305**_a_-**305**_d_ may also contain a number of component converters, for example a serial connection of a buck and a boost converter. Each converter **305**_a_-**305**_d_ includes a control loop **323**_i_ that receives a feedback signal, not from the converter's output current or voltage, but rather from the converter's input coming from the solar panel **301**. An example of such a control loop is a maximum power point tracking (MPPT) loop. The MPPT loop in the converter locks the input voltage and current from each solar panel **301**_a_-**301**_d_ to its optimal power point.

Conventional DC-to-DC converters may have a wide input voltage range at their input and an output voltage that is predetermined and fixed. In these conventional DC-to-DC voltage converters, a controller within the converter monitors the current or voltage at the input, and the voltage at the output. The controller determines the appropriate pulse width modulation (PWM) duty cycle to fix the output voltage to the predetermined value by increasing the duty cycle if the output voltage drops. Accordingly, the conventional converter includes a feedback loop that closes on the output voltage and uses the output voltage to further adjust and fine tune the output voltage from the converter. As a result of changing the output voltage, the current extracted from the input is also varied.

In the converters **305**_a_-**305**_d_, according to aspects of the present invention, a controller within the converter **405** monitors the voltage and current at the converter input and determines the PWM in such a way that maximum power is extracted from the attached panel **301**_a_-**301**_d_. The controller of the converter **405** dynamically tracks the maximum power point at the converter input. In the aspects of the present invention, the feedback loop is closed on the input power in order to track maximum input power rather than closing the feedback loop on the output voltage as performed by conventional DC-to-DC voltage converters.

As a result of having a separate MPPT circuit in each converter **305**_a_-**305**_d_, and consequently for each solar panel **301**_a_-**301**_d_, each string **303** in the embodiment shown in FIG. **3** may have a different number or different brand of panels **301**_a_-**301**_d_ connected in series. The circuit of FIG. **3** continuously performs MPPT on the output of each solar panel **301**_a_-**301**_d_ to react to changes in temperature, solar radiance, shading or other performance factors that impact that particular solar panel **301**_a_-**301**_d_. As a result, the MPPT circuit within the converters **305**_a_-**305**_d_ harvests the maximum possible power from each panel **301**_a_-**301**_d_ and transfers this power as output regardless of the parameters impacting the other solar panels.

As such, the aspects of the invention shown in FIG. **3** continuously track and maintain the input current and the input voltage to each converter at the maximum power point of the DC power source providing the input current and the input voltage to the converter. The maximum power of the DC power source that is input to the converter is also output from the converter. The converter output power may be at a current and voltage different from the converter input current and voltage. The output current and voltage from the converter are responsive to requirements of the series connected portion of the circuit.

In one aspect of the invention, the outputs of converters **305**_a_-**305**_d_ are series connected into a single DC output that forms the input to the load or power supplier, in this example, inverter **304**. The inverter **304** converts the series connected DC output of the converters into an AC power supply. The load, in this case inverter **304**, regulates the voltage at the load's input. That is, in this example, an independent control loop **321** holds the input voltage at a set value, say 400 volts. Consequently, the inverter's input current is dictated by the available power, and this is the current that flows through all serially connected DC sources. On the other hand, while the output of the DC-DC converters must be at the inverter's current input, the current and voltage input to the converter is independently controlled using the MPPT.

In the conventional art, the input voltage to the load was allowed to vary according to the available power. For example, when a lot of sunshine is available in a solar installation, the voltage input to the inverter can vary even up to 1000 volts. Consequently, as sunshine illumination varies, the voltage varies with it, and the electrical components in the inverter (or other power supplier or load) are exposed to varying voltage. This tends to degrade the performance of the components and ultimately causes them to fail. On the other hand, by fixing the voltage or current to the input of the load or power supplier, here the inverter, the electrical components are always exposed to the same voltage or 30 current and therefore would have extended service life. For example, the components of the load (e.g., capacitors, switches and coil of the inverter) may be selected so that at the fixed input voltage or current they operate at, say, 60% of their rating. This would improve the reliability and prolong the service life of the component, which is critical for avoiding loss of service in applications such as solar power systems.

FIGS. **4**A and **4**B illustrate the operation of the system of FIG. **3** under different conditions, according to aspects of the invention. The exemplary configuration **40** is similar to configuration **30** of FIG. **3**. In the example shown, ten DC power sources **401/1** through **401/10** are connected to ten power converters **405/1** through **405/10**, respectively. The modules formed by the DC power sources and their corresponding converters arc coupled together in series to form a string **403**. In one aspect of the invention, the series-connected converters **405** are coupled to a DC-to-AC inverter **404**.

The DC power sources may be solar panels and the example is discussed with respect to solar panels as one illustrative case. Each solar panel **401** may have a different power output due to manufacturing tolerances, shading, or other factors. For the purpose of the present example, an ideal case is illustrated in FIG. **4**A, where efficiency of the DC-to-DC conversion is assumed to be 100% and the panels **501** are assumed to be identical. In some aspects of the invention, efficiencies of the converters may be quite high and range at about 95%-99%. So, the assumption of 100% efficiency is not unreasonable for illustration purposes. Moreover, according to embodiments of the subject invention, each of the DC-DC converters are constructed as a power converter, i.e., it transfers to its output the entire power it receives in its input with very low losses.

Power output of each solar panel **401** is maintained at the maximum power point for the panel by a control loop within the corresponding power converter **405**. In the example shown in FIG. **4**A, all of the panels are exposed to full sun illumination and each solar panel **401** provides 200 W of power. Consequently, the MPPT loop will draw current and voltage level that will transfer the entire 200 W from the panel to its associated converter.

That is, the current and voltage dictated by the MPPT form the input current I in, and input voltage V in to the converter. The output voltage is dictated by the constant voltage set at the inverter **404**, as will be explained below. The output current I out would then be the total power, i.e., 200 W, divided by the output voltage V out.

As noted above, according to a feature of the invention, the input voltage to inverter **404** is controlled by the inverter (in this example, kept constant), by way of control loop **421**. For the purpose of this example, assume the input voltage is kept as 400V (ideal value for inverting to 220VAC). Since we assume that there are ten serially connected power converters, each providing 200 W, we can see that the input current to the inverter **404** is 2000 W/400V=5 A. Thus, the current flowing through each of the converters **401/1-401/10** must be 5 A. This means that in this idealized example each of the converters provides an output voltage of 200 W/5 A=40V. Now, assume that the MPPT for each panel (assuming perfect matching panels) dictates V MPP=32V. This means that the input voltage to the inverter would be 32V, and the input current would be 200 W/32V=6.25 A.

We now turn to another example, wherein the system is still maintained at an ideal mode (i.e., perfectly matching DC sources and entire power is transferred to the inverter), but the environmental conditions are not ideal. For example, one DC source is overheating, is malfunctioning, or, as in the example of FIG. **4**B, the ninth solar panel **401/9** is shaded and consequently produces only 40 W of power. Since we keep all other conditions as in the example of FIG. **4**A, the other nine solar panels **401** are unshaded and still produce 200 W of power. The power converter **405/9** includes MPPT to maintain the solar panel **501/9** operating at the maximum power point, which is now lowered due to the shading.

The total power available from the string is now 9×200 W+40 W=1840 W. Since the input to the inverter is still maintained at 400V, the input current to the inverter will now be 1840 W/40V=4.6 A. This means that the output of all of the power converters **405/1-405/10** in the string must be at 4.6 A. Therefore, for the nine unshaded panels, the converters will output 200 W/4.6 A=43.5V. On the other hand, the converter **405/9** attached to the shaded panel **401/9** will output 40 W/4.6 A=8.7V. Checking the math, the input to the inverter can be obtained by adding nine converters providing 43.5V and one converter providing 8.7V, i.e., (9×43.5V)+8.7V=400V.

The output of the nine non-shaded panels would still be controlled by the MPPT as in FIG. **4**A, thereby standing at 32V and 6.25 A. On the other hand, since the nines panes **401/9** is shaded, let's assume its MPPT dropped to 28V. Consequently, the output current of the ninth panel is 40 W/28V=1.43 A. As can be seen by this example, all of the panels are operated at their maximum power point, regardless of operating conditions. As shown by the example of FIG. **4**B, even if the output of one DC source drops dramatically, the system still maintains relatively high power output by fixing the voltage input to the inverter, and controlling the input to the converters independently so as to draw power from the DC source at the MPP.

As can be appreciated, the benefit of the topology illustrated in FIGS. **4**A and **4**B are numerous. For example, the output characteristics of the serially connected DC sources, such as solar panels, need not match. Consequently, the serial string may utilize panels from different manufacturers or panels installed on different parts of the roofs (i.e., at different spatial orientation). Moreover, if several strings are connected in parallel, it is not necessary that the strings match; rather each string may have different panels or different number of panels. This topology also enhances reliability by alleviating the hot spot problem. That is, as shown in FIG. **4**A the output of the shaded panel **401/9** is 1.43 A, while the current at the output of the unshaded panels is 6.25 A. This discrepancy in current when the components are series connected causes a large current being forced through the shaded panel that may cause overheating and malfunction at this component. However, by the inventive topology wherein the input voltage is set independently, and the power draw from each panel to its converter is set independently according to the panels MPP at each point in time, the current at each panel is independent on the current draw from the serially connected converters.

It is easily realized that since the power is optimized independently for each panel, panels could be installed in different facets and directions in BIPV installations. Thus, the problem of low power utilization in building-integrated installations is solved, and more installations may now be profitable.

The described system could also easily solve the problem of energy harvesting in low light conditions. Even small amounts of light are enough to make the converters **405** operational, and they then start transferring power to the inverter. If small amounts of power are available, there will be a low current flow—but the voltage will be high enough for the inverter to function, and the power will indeed be harvested.

According to aspects of the invention, the inverter **404** includes a control loop **421** to maintain an optimal voltage at the input of inverter **404**. In the example of FIG. **4**B, the input voltage to inverter **404** is maintained at 400V by the control loop **421**. The converters **405** are transferring substantially all of the available power from the solar panels to the input of the inverter **404**. As a result, the input current to the inverter **404** is dependent only on the power provided by the solar panels and the regulated set, i.e., constant, voltage at the inverter input.

The conventional inverter **104**, shown in FIG. **1** and FIG. **3**, is required to have a very wide input voltage to accommodate for changing conditions, for example a change in luminance, temperature and aging of the solar array. This is in contrast to the inverter **404** that is designed according to aspects of the present invention. The inverter **404** does not require a wide input voltage and is therefore simpler to design and more reliable. This higher reliability is achieved, among other factors, by the fact that there are no voltage spikes at the input to the inverter and thus the components of the inverter experience lower electrical stress and may last longer.

When the inverter **404** is a part of the circuit, the power from the panels is transferred to a load that may be connected to the inverter. To enable the inverter **404** to work at its optimal input voltage, any excess power produced by the solar array, and not used by the load, is dissipated. Excess power may be handled by selling the excess power to the utility company if such an option is available. For off-grid solar arrays, the excess power may be stored in batteries. Yet another option is to connect a number of adjacent houses together to form a micro-grid and to allow load-balancing of power between the houses. If the excess power available from the solar array is not stored or sold, then another mechanism may be provided to dissipate excess power.

The features and benefits explained with respect to FIGS. **4**A and **4**B stem, at least partially, from having the inverter dictates the voltage provided at its input. Conversely, a design can be implemented wherein the inverter dictates the current at its input. Such an arrangement is illustrated in FIG. **4**C. FIG. **4**C illustrates an embodiment of the invention wherein the inverter controls the input current. Power output of each solar panel **401** is maintained at the maximum power point for the panel by a control loop within the corresponding power converter **405**. In the example shown in FIG. **4**C, all of the panels are exposed to full sun illumination and each solar panel **401** provides 200 W of power. Consequently, the MPPT loop will draw current and voltage level that will transfer the entire 200 W from the panel to its associated converter. That is, the current and voltage dictated by the MPPT form the input current I in and input voltage V in to the converter. The output voltage is dictated by the constant current set at the inverter **404**, as will be explained below. The output voltage V_{out} would then be the total power, i.e., 200 W, divided by the output current I_{out}.

As noted above, according to a feature of the invention, the input current to inverter **404** is dictated by the inverter by way of control loop **421**. For the purpose of this example, assume the input current is kept as 5 A. Since we assume that there are ten serially connected power converters, each providing 200 W, we can see that the input voltage to the inverter **404** is 2000 W/5 A=400V. Thus, the current flowing through each of the converters **401/1-401/10** must be 5 A. This means that in this idealized example each of the converters provides an output voltage of 200 W/5 A=40V. Now, assume that the MPPT for each panel (assuming perfect matching panels) dictates V MPP=32V. This means that the input voltage to the inverter would be 32V, and the input current would be 10 200 W/32V=6.25 A.

Consequently, similar advantages have been achieved by having the inverter control the current, rather than the voltage. However, unlike the conventional art, changes in the output of the panels will not cause in changes in the current flowing to the inverter, as that is dictated by the inverter itself. Therefore, if the inverter is designed to keep the current or the voltage constant, then regardless of the operation of the panels, the current or voltage to the inverter will remain constant.

FIG. **5** illustrates a distributed power harvesting system, according to other aspects of the invention, using DC power sources. FIG. **5** illustrates multiple strings **503** coupled together in parallel. Each of the strings is a series connection of multiple modules and each of the modules includes a DC power source **501** that is coupled to a converter **505**. The DC power source may be a solar panel. The output of the parallel connection of the strings **503** is connected, again in parallel, to a shunt regulator **506** and a load controller **504**. The load controller **504** may be an inverter as with the embodiments of FIGS. **4**A and **4**B. Shunt regulators automatically maintain a constant voltage across its terminals.

The shunt regulator **506** is configured to dissipate excess power to maintain the input voltage at the input to the inverter **504** at a regulated level and prevent the inverter input voltage from increasing. The current which flows through shunt regulator **506** complements the current drawn by inverter **504** in order to ensure that the input voltage of the inverter is maintained at a constant level, for example at 400V.

By fixing the inverter input voltage, the inverter input current is varied according to the available power draw. This current is divided between the strings **503** of the series connected converters. When each converter includes a controller loop maintaining the converter input voltage at the maximum power point of the associated DC power source, the output power of the converter is determined. The converter power and the converter output current together determine the converter output voltage. The converter output voltage is used by a power conversion circuit in the converter for stepping up or stepping down the converter input voltage to obtain the converter output voltage from the input voltage as determined by the MPPT.

FIG. **6** illustrates an exemplary DC-to-DC converter **605** according to aspects of the invention. DC-to-DC converters arc conventionally used to either step down or step up a varied or constant DC voltage input to a higher or a lower constant voltage output, depending on the requirements of the circuit. However, in the embodiment of FIG. **6** the DC-DC converter is used as a power converter, i.e., transferring the input power to output power, the input voltage varying according to the MPPT, while the output current being dictated by the constant input voltage to the inverter. That is, the input voltage and current may vary at any time and the output voltage and current may vary at any time, depending on the operating condition of the DC power sources.

The converter **605** is connected to a corresponding DC power source **601** at input terminals **614** and **616**. The converted power of the DC power source **601** is output to the circuit through output terminals **610**, **612**. Between the input terminals **614**, **616** and the output terminals **610**, **612**, the remainder of the converter circuit is located that includes input and output capacitors **620**, **640**, back flow prevention diodes **622**, **642** and a power conversion circuit including a controller **606** and an inductor **608**.

The inputs **616** and **614** are separated by a capacitor **620** which acts as an open to a DC voltage. The outputs **610** and **612** are also separated by a capacitor **640** that also acts an open to DC output voltage. These capacitors are DC-blocking or AC-coupling capacitors that short when faced with alternating current of a frequency for which they are selected. Capacitor **640** coupled between the outputs **610**, **612** and also operates as a part of the power conversion circuit discussed below.

Diode **642** is coupled between the outputs **610** and **612** with a polarity such that current may not backflow into the converter **605** from the positive lead of the output **612**. Diode **622** is coupled between the positive output lead **612** through inductor **608** which acts a short for DC current and the negative input lead **614** with such polarity to prevent a current from the output **612** to backflow into the solar panel **601**.

The DC power sources **601** may be solar panels. A potential difference exists between the wires **614** and **616** due to the electron-hole pairs produced in the solar cells of panel **601**. The converter **605** maintains maximum power output by extracting current from the solar panel **601** at its peak power point by continuously monitoring the current and voltage provided by the panel and using a maximum power point tracking algorithm. The controller **606** includes an MPPT circuit or algorithm for performing the peak power tracking. Peak power tracking and pulse width modulation, PWM, are performed together to achieve the desired input voltage and current. The MPPT in the controller **606** may be any conventional MPPT, such as, e.g, perturb and observe (P&O), incremental conductance, etc. However, notably the MPPT is performed on the panel directly, i.e., at the input to the converter, rather than at the output of the converter. The generated power is then transferred to the output terminals **610** and **612**. The outputs of multiple converters **605** may be connected in series, such that the positive lead **612** of one converter **605** is connected to the negative lead **610** of the next converter **605**.

In FIG. **6**, the converter **605** is shown as a buck plus boost converter. The term "buck plus boost" as used herein is a buck converter directly followed by a boost converter as shown in FIG. **6**, which may also appear in the literature as "cascaded buck-boost converter". If the voltage is to be lowered, the boost portion is substantially shorted. If the voltage is to be raised, the buck portion is substantially shorted. The term "buck plus boost" differs from buck/boost topology which is a classic topology that may be used when voltage is to be raised or lowered. The efficiency of "buck/boost" topology is inherently lower than a buck or a boost. Additionally, for given requirements, a buck-boost converter will need bigger passive components then a buck plus boost converter in order to function. Therefore, the buck plus boost topology of FIG. **6** has a higher efficiency than the buck/boost topology. However, the circuit of FIG. **6** continuously decides whether it is bucking or boosting. In some situations when the desired output voltage is similar to the input voltage, then both the buck and boost portions may be operational.

The controller **606** may include a pulse width modulator, PWM, or a digital pulse width modulator, DPWM, to be used with the buck and boost converter circuits. The controller **606** controls both the buck converter and the boost converter and determines whether a buck or a boost operation is to be performed. In some circumstances both the buck and boost portions may operate together. That is, as explained with respect to the embodiments of FIGS. **4**A and **4**B, the input voltage and current are selected independently of the selection of output current and voltage. Moreover, the selection of either input or output values may change at any given moment depending on the operation of the DC power sources. Therefore, in the embodiment of FIG. **6** the converter is constructed so that at any given time a selected value of input voltage and current may be up converted or down converted depending on the output requirement.

In one implementation, an integrated circuit (IC) **604** may be used that incorporates some of the functionality of converter **605**. IC **604** is optionally a single ASIC able to withstand harsh temperature extremes present in outdoor solar installations. ASIC **604** may be designed for a high mean time between failures (MTBF) of more than 25 years. However, a discrete solution using multiple integrated circuits may also be used in a similar manner. In the exemplary embodiment shown in FIG. **6**, the buck plus boost portion of the converter **605** is implemented as the IC **604**. Practical considerations may lead to other segmentations of the system. For example, in one aspect of the invention, the IC **604** may include two ICs, one analog IC which handles the high currents and voltages in the system, and one simple low-voltage digital IC which includes the control logic. The analog IC may be implemented using power FETs which may alternatively be implemented in discrete components, FET drivers, A/Ds, and the like. The digital IC may form the controller **606**.

In the exemplary circuit shown, the buck converter includes the input capacitor **620**, transistors **628** and **630** a diode **622** positioned in parallel to transistor **628**, and an inductor **608**. The transistors **628**, **630** each have a parasitic body diode **624**, **626**. In the exemplary circuit shown, the boost converter includes the inductor **608**, which is shared with the buck converter, transistors **648** and **650** a diode **642** positioned in parallel to transistor **650**, and the output capacitor **640**. The transistors **648**, **650** each have a parasitic body diode **644**, **646**.

As shown in FIG. **1**, adding electronic elements in the series arrangement may reduce the reliability of the system, because if one electrical component breaks it may affect the entire system. Specifically, if a failure in one of the serially connected elements causes an open circuit in the failed element, current ceases to flow through the entire series, thereby causing the entire system to stop function. Aspects of the present invention provide a converter circuit where electrical elements of the circuit have one or more bypass routes associated with them that carry the current in case of the electrical element fails. For example, each switching transistor of either the buck or the boost portion of the converter has its own bypass. Upon failure of any of the switching transistors, that element of the circuit is bypassed. Also, upon inductor failure, the current bypasses the failed inductor through the parasitic diodes of the transistor used in the boost converter.

FIG. **7** illustrates a power converter, according to aspects of the invention. FIG. **7** highlights, among others, a monitoring and control functionality of a DC-to-DC converter **705**, according to embodiments of the present invention. A DC voltage source **701** is also shown in the figure. Portions of a simplified buck and boost converter circuit are shown for the converter **705**. The portions shown include the switching transistors **728**, **730**, **748** and **750** and the common inductor **708**. Each of the switching transistors is controlled by a power conversion controller **706**.

The power conversion controller **706** includes the pulse-width modulation (PWM) circuit **733**, and a digital control machine **730** including a protection portion **737**. The power conversion controller **706** is coupled to microcontroller **790**, which includes an MPPT module **719**, and may also optionally include a communication module **709**, a monitoring and logging module **711**, and a protection module **735**.

A current sensor **703** may be coupled between the DC power source **701** and the converter **705**, and output of the current sensor **703** may be provided to the digital control machine **730** through an associated analog to digital converter **723**. A voltage sensor **704** may be coupled between the DC power source **701** and the converter **705** and output of the voltage sensor **704** may be provided to the digital control machine **730** through an associated analog to digital converter **724**. The current sensor **703** and the voltage sensor **704** are used to monitor current and voltage output from the DC power source, e.g., the solar panel **701**. The measured current and voltage are provided to the digital control machine **730** and are used to maintain the converter input power at the maximum power point.

The PWM circuit **733** controls the switching transistors of the buck and boost portions of the converter circuit. The PWM circuit may be a digital pulse-width modulation (DPWM) circuit. Outputs of the converter **705** taken at the inductor **708** and at the switching transistor **750** are provided to the digital control machine **730** through analog to digital converters **741**, **742**, so as to control the PWM circuit **733**.

A random access memory (RAM) module **715** and a non-volatile random access memory (NVRAM) module **713** may be located outside the microcontroller **790** but coupled to the microcontroller **790**. A temperature sensor **779** and one or more external sensor interfaces **707** may be coupled to the microcontroller **790**. The temperature sensor **779** may be used to measure the temperature of the DC power source **701**. A physical interface **717** may be coupled to the microcontroller **790** and used to convert data from the microcontroller into a standard communication protocol and physical layer. An internal power supply unit **739** may be included in the converter **705**.

In various aspects of the invention, the current sensor **703** may be implemented by various techniques used to measure current. In one aspect of the invention, the current measurement module **703** is implemented using a very low value resistor. The voltage across the resistor will be proportional to the current flowing through the resistor. In another aspect of the invention, the current measurement module **703** is implemented using current probes which use the Hall Effect to measure the current through a conductor without adding a series resistor. After translating the current to voltage, the data may be passed through a low pass filter and then digitized. The analog to digital converter associated with the current sensor **703** is shown as the A/D converter **723** in FIG. **7**. Aliasing effect in the resulting digital data may be avoided by selecting an appropriate resolution and sample rate for the analog to digital converter. If the current sensing technique does not require a series connection, then the current sensor **703** may be connected to the DC power source **701** in parallel.

In one aspect of the invention, the voltage sensor **704** uses simple parallel voltage measurement techniques in order to measure the voltage output of the solar panel. The analog voltage is passed through a low pass filter in order to minimize aliasing. The data is then digitized using an analog to digital converter. The analog to digital converter associated with the voltage sensor **704** are shown as the A/D converter in FIG. **7**. The A/D converter **724** has sufficient resolution to generate an adequately sampled digital signal from the analog voltage measured at the DC power source **701** that may be a solar panel.

The current and voltage data collected for tracking the maximum power point at the converter input may be used for monitoring purposes also. An analog to digital converter with sufficient resolution may correctly evaluate the panel voltage and current. However, to evaluate the state of the panel, even low sample rates may be sufficient. A low-pass filter makes it possible for low sample rates to be sufficient for evaluating the state of the panel. The current and voltage date may be provided to the monitoring and logging module **711** for analysis.

The temperature sensor **779** enables the system to use temperature data in the analysis process. The temperature is indicative of some types of failures and problems. Furthermore, in the case that the power source is a solar panel, the panel temperature is a factor in power output production.

The one or more optional external sensor interfaces **707** enable connecting various external sensors to the converter **705**. External sensors are optionally used to enhance analysis of the state of the solar panel **701**, or a string or an array formed by connecting the solar panels **701**.

Examples of external sensors include ambient temperature sensors, solar radiance sensors, and sensors from neighboring panels. External sensors may be integrated into the converter **705** instead of being attached externally.

In one aspect of the invention, the information acquired from the current and voltage sensors **703**, **704** and the optional temperature and external sensors **705**, **707** may be transmitted to a central analysis station for monitoring, control, and analysis using the communications interface **709**. The central analysis station is not shown in the figure. The communication interface **709** connects a microcontroller **790** to a communication bus.

The communication bus can be implemented in several ways. In one aspect of the invention, the communication bus is implemented using an off-the-shelf communication bus such as Ethernet or RS422. Other methods such as wireless communications or power line communications, which could be implemented on the power line connecting the panels, may also be used. If bidirectional communication is used, the central analysis station may request the data collected by the microcontroller **790**. Alternatively or in addition, the information acquired from sensors **703**, **704**, **705**, **707** is logged locally using the monitoring and logging module **711** in local memory such as the RAM **715** or the NVRAM **713**.

Analysis of the information from sensors **703**, **704**, **705**, **707** enables detection and location of many types of failures associated with power loss in solar arrays. Smart analysis can also be used to suggest corrective measures such as cleaning or replacing a specific portion of the solar array. Analysis of sensor information can also detect power losses caused by environmental conditions or installation mistakes and prevent costly and difficult solar array testing.

Consequently, in one aspect of the invention, the microcontroller **790** simultaneously maintains the maximum power point of input power to the converter **705** from the attached DC power source or solar panel **701** based on the MPPT algorithm in the MPPT module **719** and manages the process of gathering the information from sensors **703**, **704**, **705**, **707**. The collected information may be stored in the local memory **713**, **715** and transmitted to an external central analysis station In one aspect of the invention, the microcontroller **790** uses previously defined parameters stored in the NVRAM **713** in order to operate. The information stored in the NVRAM **713** may include information about the converter **705** such as serial number, the type of communication bus used, the status update rate and the ID of the central analysis station. This information may be added to the parameters collected by the sensors before transmission.

The converters **705** may be installed during the installation of the solar array or retrofitted to existing installations. In both cases, the converters **705** may be connected to a panel junction connection box or to cables connecting the panels **701**. Each converter **705** may be provided with the connectors and cabling to enable easy installation and connection to solar panels **701** and panel cables.

In one aspect of the invention, the physical interface **717** is used to convert to a standard communication protocol and physical layer so that during installation and maintenance, the converter **705** may be connected to one of various data terminals, such as a computer or PDA. Analysis may then be implemented as software which will be run on a standard computer, an embedded platform or a proprietary device.

The installation process of the converters **705** includes connecting each converter **705** to a solar panel **701**. One or more of the sensors **703**, **704**, **705**, **707** may be used to ensure that the solar panel **701** and the converter **705** are properly coupled together. During installation, parameters such as serial number, physical location and the array connection topology may be stored in the NVRAM **713**. These parameters may be used by analysis software to detect future problems in solar panels **701** and arrays.

When the DC power sources **701** are solar panels, one of the problems facing installers of photovoltaic solar panel arrays is safety. The solar panels **701** are connected in series during the day when there is sunlight. Therefore, at the final stages of installation, when several solar panels **701** are connected in series, the voltage across a string of panels may reach dangerous levels. Voltages as high as 600V are common in domestic installations. Thus, the installer faces a danger of electrocution. The converters **705** that are connected to the panels **701** may use built-in functionality to prevent such a danger. For example, the converters **705** may include circuitry or hardware of software safety module that limits the output voltage to a safe level until a predetermined minimum load is detected. Only after detecting this predetermined load, the microcontroller **790** ramps up the output voltage from the converter **705**.

Another method of providing a safety mechanism is to use communications between the converters **705** and the associated inverter for the string or array of panels. This communication, that may be for example a power line communication, may provide a handshake before any significant or potentially dangerous power level is made available. Thus, the converters **705** would wait for an analog or digital release signal from the inverter in the associated array before transferring power to inverter.

The above methodology for monitoring, control and analysis of the DC power sources **701** may be implemented on solar panels or on strings or arrays of solar panels or for other power sources such as batteries and fuel cells.

Use of Battery as DC Power Source/Sink

A typical rechargeable battery may be made with serially connected secondary cells and in some cases, several parallel strings of serially connected cells. Serially connected secondary cells are used to build a battery voltage high enough to fit a specific application voltage. A typical generic charging application applied to a rechargeable battery, may include a bulk power source which provides raw DC power to the rechargeable battery and a regulator which regulates current and/or voltage applied to the rechargeable battery. For less-expensive chargers, the regulator is usually a power transistor or other linear-pass element that dissipates power as heat. The regulator may also be a buck switching supply that includes a standard freewheeling diode for average efficiency or a synchronous rectifier for highest efficiency. The typical generic charging application may further include a current-control loop which limits the maximum current delivered to the battery, and a voltage loop which maintains a constant voltage on the battery. (Note that Li+ cells typically require a high level of precision in the applied charging voltage.) Also the current-voltage (I-V) characteristic may be fully programmable, or may be programmable in current only, with a voltage limit (or vice versa). Cell temperature of the battery may be measured, and charge termination can be based either on the level or the slope of this measurement. Charging time may be measured, usually as a calculation in an intelligence block such as microprocessor with memory for example. The intelligence block provides intelligence for the system and typically implements a state machine. The intelligence block using the state machine knows how and when to terminate a charge. Discharge is done, usually, directly from a cell array, via current sensing (in order to keep track of actual battery charge).

A serial connection of battery cells may pose a challenge in managing the charge and discharge of battery cells. All cells typically must be matched in terms of electrical characteristics and initial charge levels. Cells also need to be matched thermally otherwise the same electrical conditions can have different (and catastrophic) results for different cells Usually several temperature sensors are used to meet the needed safety requirements but the typical outcome is that the entire battery charge performance is limited by the weakest cell. Adding several parallel strings of cells may be an additional challenge, since impedance of all cells arc low, any small impedance difference may result in a large variance in current between strings. The large variance in current between strings may be difficult to manage without some separate circuit hardware per string.

Reference is now made to FIG. **3***a* which show system **30***a* according to an embodiment of the present invention. System **30***a* includes converters **305***a*-**305***d* with terminals connected in series to form a string **3003**, the same as shown in configuration **30** (FIG. **3**). The other terminals of converters **305***a*-**305***d* are connected to re-chargeable cells **6001***a*-**6001***d* respectively to form a module **320***a*. Each module **320***a* includes a control loop **323***i* that receives a feedback signal, from the connection between a converter **305** and a cell **6001**. Loop **323***i* typically determines the voltage across the connection between converter **305** and cell **6001** and/or the current between converter **305** and cell **6001**. String **3003** is connected to a terminal of power controller **3004***a*. Several strings **3003** may be further connected to the terminal of power controller **3004***a* by connecting strings **3003** in parallel. The other terminal **330** of power controller **3004** may be connected to a power supply or a load. The power supply may be an AC supply such as a grid voltage or a DC supply. The load may be an AC load or a DC load. System **30***a* typically operates in two modes. One mode is the discharge of cells **6001** to supply the load or the power supply connected to power controller **3004***a*. The other mode is to charge cells **6001** via power controller **3004***a* when controller **3004***a* is connected to the power supply. During charging of cells **6001**, controller **3004***a* typically operates as a parallel charger. Controller **3004***a* acts as a voltage source that supplies any amount of power up to the total power available by the power source. The voltage source can be fixed to almost any voltage and can be optimized depending on the amount of modules **320***a*. Power controller **3004***a* may be DC to AC inverter or a DC to DC converter the same as a converter **305** for example. According to a feature of the present invention an independent control loop **321***a* of controller **3004***a* typically holds the voltage of string **3003** at a set value.

Reference is now made to FIG. **3***b* which shows system **30***b* according to an embodiment of the present invention. System **30***a* includes converters **305***a*-**305***d* with terminals connected in series to form a string **3003**, the same as show in configuration **30***a* (shown in FIG. **3***a*). The other terminals of converters **305***a*-**305***d* are connected to re-chargeable cells **6001***a*-**6001***d* respectively to form a module **320***a*. Each module **320***a* includes two control loops **323***i* and **323***o*. Converter **305** may independently choose which loop **323***i* or **323***o* to use for operation of converter **305**. Converter **305** may also operate control loops **323***i* and **323***o* simultaneously, such that loop **323***i* determines the voltage and current of battery **6001** and hence the power (P) of battery **6001**. Whilst at the same time, loop **323***o* determines the voltage and current of converter **305** and therefore power in string **3003**. The voltages and currents on either side of converter **305** change respectively in order to preserve maximum power through converter **305**. Converter **3004***a* typically may be another DC-DC converter **305** without loops **323***i* and **323***o* or may be a DC-AC inverter. Loop **323***i* provides a feedback signal to converter **305**, from the connection between converter **305** and cell **6001**. Loop **323***i* typically determines the voltage across the connection between converter **305** and cell **6001** and/or the direction of current (i.e. charging or discharging) between converter **305** and cell **6001**. Loop **323***o* provides a feedback signal to converter **305** from string **3003**. Loop **323***o* typically determines the voltage contribution of converter **305** to string **3003** and/or the direction of current to converter **305**.

String **3003** is connected to converter **3004***a*. Several strings **3003** may be further connected to converter **3004***a* by connecting strings **3003** in parallel. The other side **330** of converter **3004** may be connected to a power supply or a load. The power supply may be an AC supply such as a grid voltage or a DC supply. The load may be an AC load or a DC load. System **30***b* typically operates in two modes. One mode is the discharge of cells **6001** to supply the load or the power supply connected to converter **3004***a*. The other mode is to charge cells **6001** via converter **3004***a* connected to the power supply. During charging of cells **6001**, converter **3004***a* typically operates as a simplified parallel charger. Converter **3004***a* acts as a voltage source that supplies any amount of power up to the total power available by the power source. The voltage source can be fixed to almost any voltage and can be optimized depending on the number of modules **320***a*.

Reference is now made to FIG. **3***c* which show system **30***c* according to an embodiment of the present invention. System **30***c* includes converters **305***a*-**305***d* with terminals connected in series to form a string **3003**, the same as show in configuration **30***a* (shown in FIG. **3***a*). The other terminals of converters **305***a*-**305***d* are connected to re-chargeable cells **6001***a*-**6001***d* respectively to form a module **320***a*. Each module **320***a* includes battery **6001**, converter **305**, and control loop **323***i*. Serial string of modules **320***a* is connected in parallel with a second serial string **303** of modules **320** including photovoltaic panel **301**, and converter **305** each with control loop **323***i*. The two serial strings are connected to power converter **3004***a* which may be a grid connected DC-AC inverter or DC-DC converter on connection **330** for instance. Power converter **3004***a* is shown with a control loop **321***a* which sets the voltage or current in the parallel-connected serial strings at a previously determined value generally dependent on the direction of current flow, i.e. charging or discharging. System **30***c* may be used for grid-connected or off grid applications. In particular, photovoltaic module string **303** may be used to charge batteries of battery string **3003**. The energy stored in battery string **3003** may be sold to the grid at a later time for instance when the electricity price tariffs are higher.

During charging a converter **305** acts as an optimized charger for a battery **6001**. Charging a battery **6001** is preferably performed by controlling the current (I)/voltage **30** (V) characteristics of a charge profile for a converter **305**, to feed into a battery **6001** the most favorable charge power needed at any given time. Converter **305** may also act as a current source, perform voltage regulation or trickle charge depending on need. One side of each converter **305** may draw a different power from controller **3004***a*, depending on power needed by a battery **6001** connected to the other side of converter **305**. By sharing the same battery string **3003** current, the voltage of each converter **305** in battery string **3003** will typically be different for each converter **305**. The total voltage provided by string **3003** will typically be the voltage set by controller **3004***a*. If a battery is fully charged, converter **305** will enter a bypass mode in which it is not taking power from controller **3004***a*. Controller **3004***a* may also turn ON or OFF any number of converters **305** in case controller **3004***a* does not have enough power to charge all batteries **6001**. In an optimal way, controller **3004***a* can shut OFF some of converters **305** leaving only some of batteries **6001** to be charged. Once batteries **6001** are fully charged converters **305** will shut OFF and other batteries **6001** can be charged. By charging some batteries **6001** and not other batteries **6001** means batteries **6001** are always charged in the most efficient way independent of the amount of power available for charging. Controller **3004***a* communicates with converters **305** via power line communication so additional wires are not needed for charge control of batteries **6001**.

Discharge of batteries **6001** is very similar to harvesting power from different rated photovoltaic modules (PV) modules **301** and/or PV strings **303**. Controller **3004***a* regulates the string **3003** voltage to a fixed voltage. Each converter **305** will discharge the power in battery **6001**. Controller **3004***a* may increase or decrease the total amount of power drawn via communication with converters **305** so that the total power supplied is equal to the load needed. Each converter **305** will supply the energy available from its battery **6001**. By sharing the same string **3003** current, the voltage of each converter **305** on the side connected to controller **3004***a* will be different for each converter **305**. The total voltage across string **3004***a* is typically set by controller **3004***a*.

Reference is now made to FIG. **6***a* which shows a slightly modified DC-DC converter **305** based on the DC-DC converter **605** shown in FIG. **6**, according to an embodiment of the present invention. Converter **305** additionally includes high frequency transducer **62** and low frequency transducer **63** placed in negative power line **614**. Transducers **62** and **63** typically include analogue to digital converters and means for power line communication or wireless communication. Transducer **62** (operatively attached to controller **606**) typically senses current in the higher frequency portion of converter **305** where switches **628**, **626**, **648**, and **646** are typically switching at a high frequency. The sensed current of transducer **62** is typically conveyed by transducer to controller **606** by wireless communication or power line communication. Transducer **63** (operatively attached to controller **606**) typically includes monitoring of current, temperature of battery **6001**. The sensed current, temperature of battery **6001** are also conveyed to controller **606** using wireless communication or power line communication. Controller **606** typically includes a microprocessor with memory. Converter **305** connects to battery **6001** with positive node **616** and negative node **614**. The other end of converter **305** has lines **614** and **612**. Multiple lines **614** and **612** of multiple converters **305** are typically joined to together in series, by connecting a line **614** of one converter with a line **612** of another converter **305** to form a battery string **3003**. A typical bypass route between power lines **612** and **610** of a converter **305** may be to have switches **650** and **644** ON and switches **630** and **628** OFF. Converter **305** is a Buck-Boost topology power converter that has the ability to control its transferred I-V curve. The topology of the converter **305** is basically symmetrical thus enabling converter **305** to convert power in either direction.

The definite articles "a", "an" is used herein, such as "a power converter", "a control loop" have the meaning of "one or more" that is "one or more power converters" or "one or more control loops".

Although selected embodiments of the present invention have been shown and described, it is to be understood the present invention is not limited to the described embodiments. Instead, it is to be appreciated that changes may be made to these embodiments without departing from the principles and spirit of the invention, the scope of which is defined by the claims and the equivalents thereof.

The invention claimed is:

1. A system comprising:

a plurality of power converters, each power converter coupled to a DC power source, wherein each power converter includes:

a control loop adapted to provide a feedback signal to the power converter from a connection between the power converter and the coupled DC power source; and

a power conversion portion adapted to perform at least one of: converting power to discharge the coupled DC power source, and converting power to charge the coupled DC power source,

wherein each of the plurality of power converters is adapted for serial connection to at least one other power converter of the plurality of power converters.

2. The system of claim **1**, wherein the control loop in each power converter is adapted to set a voltage between or current through terminals of the power converter.

3. The system of claim **1**, wherein the control loop in each power converter is adapted to lock an input voltage and current from the coupled DC power source to an optimal power point.

4. The system of claim **1**, wherein each of the plurality of power converters is configured to function as at least one of a current source, a voltage regulator, or a trickle charge source.

5. The system of claim **1**, wherein a first power converter of the plurality of power converters is coupled to a first DC power source, the first DC power source comprising a DC battery.

6. The system of claim **1**, wherein a first power converter of the plurality of power converters is coupled to a first DC power source, the first DC power source comprising a solar panel.

7. The system of claim **1**, wherein a first power converter of the plurality of power converters is coupled to a first DC power source, the first DC power source comprising a plurality of solar cells connected in series, connected in parallel, or connected in both series and parallel.

8. The system of claim **1**, wherein the plurality of power converters are configured to form a serial string of power converters, and wherein the system further comprises:

a power controller coupled to the serial string of power converters, and configured to maintain current through or voltage across the serial string of power converters at a predetermined value.

9. The system of claim **8**, wherein the power controller comprises at least one of a bi-directional DC/AC inverter, a bi-directional DC/DC converter, a charging regulator, or a load controller.

10. The system of claim **9**, further comprising a shunt regulator coupled to the serial string of power converters and to the power controller.

11. A system comprising:

a first plurality of DC power sources;

a first plurality of power converters respectively coupled to the first plurality of DC power sources, wherein each of the first plurality of power converters includes a control loop and a power conversion portion, and wherein each of the first plurality of power converters is adapted for serial connection to at least one other power converter of the first plurality of power converters, thereby forming a first serial string;

a second plurality of DC power sources; and

a second plurality of power converters respectively coupled to the second plurality of DC power sources, wherein each of the second plurality of power converters includes a control loop and a power conversion portion, and wherein each of the second plurality of power converters is adapted for serial connection to at least one other power converter of the second plurality of power converters, thereby forming a second serial string,

wherein the first serial string and the second serial string are connectible in parallel to form parallel-connected strings.

12. The system of claim **11**, wherein each control loop in each of the first plurality of power converters and each of the second plurality of power converters is configured to provide a feedback signal to the power converter from the connection between the power converter and the DC power source coupled to the power converter.

13. The system of claim **11**, wherein the first plurality of DC power sources comprise batteries.

14. The system of claim **13**, wherein the second plurality of DC power sources comprise photovoltaic panels.

15. The system of claim **11**, further comprising:

a power controller coupled in parallel to the parallel-connected strings, the power controller configured to maintain current through or voltage across the parallel-connected strings at a predetermined value.

16. The system of claim **15**, wherein the power controller is further configured to control the direction of the current and to charge the first plurality of DC power sources from the second plurality of DC power sources.

17. The system of claim **16**, wherein the power controller is further configured to:

determine that an amount of power received from the second plurality of DC power sources is insufficient to charge all of the first plurality of DC power sources; and

based on the determination, turn off one or more of the first plurality of power converters, while leaving on the remaining power converters in the first plurality of power converters when charging the first plurality of DC power sources.

18. The system of claim **16**, wherein each of the first plurality of power converters is configured to:

during the charging by the power controller, determine whether a first DC power source coupled to the power converter is full; and

based on a determination that the first DC power source is full, enter a bypass mode in which power is not taken from the power controller by the power converter.

19. The system of claim **16**, wherein the first plurality of power converters are configured to draw different amounts of power from the power controller based on power needs of their respective coupled DC power sources.

20. A method, comprising:

coupling a plurality of DC power sources respectively to a plurality of power converters, wherein each of the plurality of power converters includes:

a control loop adapted to provide a feedback signal to the power converter from a connection between the power converter and the coupled DC power source; and

a power conversion portion adapted to perform at least one of: converting power to discharge the coupled DC power source, or converting power to charge the coupled DC power source;

coupling the plurality of power converters together in a serial connection to form a serial string of power converters; and

coupling the serial string of power converters to a power controller configured to maintain current through or voltage across the serial string of power converters at a predetermined value.

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